Journal of Agriculture and Food Research 19 (2025) 101625

Contents lists available at ScienceDirect

Journal of Agriculture and Food Research

journal homepage: www.sciencedirect.com/journal/journal-of-agriculture-and-food-research

Quantifying hydrocooling water infiltration in ‘Palmer’ mangoes following hot-air quarantine treatment

Alex Guimarães Sanches [a], Maryelle Barros da Silva [a], Vanessa Maria Dantas Pedrosa [a], Thiago Feliph Silva Fernandes [a], Maria Carolina Casares Wong [a], Priscila Lupino Gratão [a], Gustavo Henrique de Almeida Teixeira [a,b,*]

[a] *Universidade Estadual Paulista (UNESP), Faculdade de Ciências Agrárias e Veterinárias (FCAV), Campus de Jaboticabal, 14.870-900, Jaboticabal, SP, Brazil*
[b] *University of Idaho (U of I), Kimberly Research and Extension Center, 83341-5082, Kimberly, ID, USA*

ARTICLE INFO

Keywords:
Mangifera indica L.
Heat treatment
Food safety
Acid blue 9 dye
Cooling

ABSTRACT

Around the world hot-air heating is used as a quarantine treatment to control fruit fly larvae in mangoes. To simulate hydrocooling water absorption in mangoes subjected to hot-air heating quarantine treatment, the internalization of acid blue 9 dye was tested. Hot-air heating fruits (45 °C) had higher acid blue 9 dye infiltration (2.26 %) compared to untreated control fruits (0.72 %). Higher dye infiltration was observed in heated fruits (2.97 %) after 15 min of cold-water immersion than the 60 min required for 1.84 % infiltration in unheated fruits. Regardless of treatment, dye infiltration occurred uniformly through the lenticels on the pericarp and occasionally through the stem into the mesocarp. Thus, hot-air heating treatment followed by immersion in cold water results in fast water infiltration, potentially allowing the internalization of food-borne pathogens if the cooling water is not properly treated.

1. Introduction

In the United States of America, quarantine treatments are mandatory to control fruit fly larvae in mangoes, with hot-air heating commonly employed worldwide [1]. Hot air is used until pulp temperature reaches a target value necessary to eliminate specific pests [2]. After this treatment, mangoes should be cooled down to mitigate the deleterious effects of hot air on metabolic processes such as transpiration, respiration, and ethylene production [3]. In this regard, hydrocooling is a common cooling technique, that employs cold water to efficiently remove heat. However, temperature differentials during hydrocooling can enhance water absorption as the volume of the fruit contracts upon cooling. This contraction creates a vacuum that pulls cold water into the fruit through natural openings, driven by pressure gradients [4,5]. In fresh products, key entry points include stem scars, stomata, lenticels, and wounds [6], which can facilitate the internalization of food-borne pathogens [7].

Larger temperature differentials amplify water absorption, but factors such as cultivars, immersion depth, and duration [8], opening type, size, hydrophobicity [9], and the presence of injuries [10] also play critical roles. For instance, papayas heated to 47 °C and cooled to approximately 25 °C showed increased mass due to water absorption [11]. Similarly, peppers harvested at 22–25 °C and cooled with 8 °C water exhibited significant water uptake [12]. In mangoes, lenticels formed from ruptured stomata during growth facilitate gas exchange and transpiration [13].

Although acid blue 9 dye has been used to simulate hydrocooling water absorption in many horticultural products [3,16], this dye has not been tested in ‘Palmer’ mangoes subjected to hot-air quarantine treatment. Thus, this study hypothesizes that hot-air treatment leads to water absorption under hydrocooling conditions. This approach not only mimics water absorption but also provides insights into the potential internalization of food-borne pathogens, thereby enhancing strategies to ensure food safety.

* Corresponding author. Universidade Estadual Paulista (UNESP), Faculdade de Ciências Agrárias e Veterinárias (FCAV), Campus de Jaboticabal, 14.870-900, Jaboticabal, SP, Brazil.

E-mail addresses: agromaryelle@gmail.com (M.B. Silva), vanessa.pedrosa@unesp.br (V.M.D. Pedrosa), thiagofeliphh@gmail.com (T.F.S. Fernandes), maria.casares@unesp.br (M.C. Casares Wong), gteixeira@uidaho.edu (G.H.A. Teixeira).

https://doi.org/10.1016/j.jafr.2024.101625
Received 18 October 2024; Received in revised form 5 December 2024; Accepted 28 December 2024
Available online 30 December 2024

2. Material and methods

2.1. Location and plant material

'Palmer' mangoes (*Mangifera indica* L.) were obtained from a commercial orchard located in Cândido Rodrigues, São Paulo, Brazil (lat. 21° 24′ 23″ S, long. 48° 30′ 20" W, 579 m altitude). Fruits were harvested at maturity stage 3, characterized by a purple green epicarp and light-yellow mesocarp. This maturity stage is commercially used to export 'Palmer' mangoes [14]. Fruits were selected to ensure uniform size (~15 cm long, average weight of 350 g), without damage, and free from pests and diseases.

2.2. Simulation of water infiltration

A total of 60 fruits were washed in running water and subsequently allowed to dry at room temperature (approximately 25 °C). These fruits were then heated in a forced air circulation chamber (Luca 82/250, Lucadema, Brazil), measuring 34 x 34 × 36 cm, with airflow velocities ranging from 0.5 to 2.0 m s^{-1}, until the pulp temperature reached 45 °C [2]. Following this heating process, ten mangoes were immediately immersed in 10 L of cold water (6 °C) containing 1 % (w/v) acid blue 9 dye (Chem-Impex International Inc., Wood Dale, IL) for intervals of 0, 5, 15, 30, 45, or 60 min [7]. Simultaneously, another batch of 60 fruits was maintained at room temperature (approximately 25 °C) and immersed in the same dye solution for equivalent durations, serving as the untreated control group. Furthermore, temperature estimation (field heat) was conducted on 10 fruits using a calibrated thermometer.

Following immersion in the dye solution, the fruits were rinsed with running water, dried with tissue paper, and subsequently stored in a cold chamber maintained at 8.0 ± 1.0 °C for 24 h. The assessment of acid blue 9 dye infiltration was conducted by longitudinally sectioning the fruits. Both halves were scanned, and the percentage of dye infiltration into the mesocarp was quantified utilizing ImageJ software. The experimental design employed was a completely randomized design (CRD) in a factorial arrangement consisting of two factors (heated and unheated) and six time intervals (0, 5, 15, 30, 45, or 60 min), with ten replicates for each treatment, resulting in a total of 120 fruits.

2.3. Statistical analysis

The dye infiltration percentage data were subjected to analysis of variance (ANOVA) using R software [15] and means were compared using the Tukey test at a significance level of 0.05 %.

3. Results and discussion

Hot-air heating fruits (45 °C) had higher acid blue 9 dye infiltration (2.3 %) compared to untreated control fruits (0.7 %). The process occurred rapidly, with higher infiltration observed in heated fruits (3.0 %) after 15 min of cold-water immersion, in contrast to 60 min required for 1.8 % infiltration in unheated fruits (Table 1). Regardless of treatment, the skin's lenticels were the main point of dye infiltration into the mesocarp (Fig. 1).

Temperature differentials promoted higher and faster acid blue 9 dye infiltration in heated fruits (45 °C) compared to fruits at ambient temperature (~25 °C). This temperature differential likely stimulated water absorption due to fruit volume expansion, creating a pressure gradient [5].

A similar study involving the absorption of acid blue 9 dye in Cantaloupe melons showed higher infiltration in melons heated to 42 °C and cooled to 6 °C compared to those heated to 18 °C [7]. 'Tommy Atkins' mangoes also exhibited higher dye infiltration rates when heated to 47 °C and cooled in colder water (24 °C) [16]. A temperature differential of 17 °C between oranges and a cooler dye solution resulted in increased dye infiltration [17]. All in all, these reports confirm that larger temperature differentials amplify water absorption. However, as internal intercellular space within the fruit is finite and not continuous, there is a limit to water entry into these spaces, which explains the dye's reduced infiltration after 15 min of immersion in cold water of fruit previously treated with hot air. The rapid water infiltration likely led to internal gas expansion, increasing its density, and reducing water absorption [18].

In general, dye infiltration into the skin occurred uniformly, possibly due to the pores (lenticels) present in this tissue [19], allowing water influx. In the mesocarp, infiltration was much lower, primarily occurring through the stem opening and occasionally spreading through vascular bundles (Fig. 1). Moreover, lenticel distribution in mangoes is 2–3 times greater in the apical region than in the middle or the shoulder [20], which can explain the greater dye internalization in this part of the fruit.

Table 1
Percentage (%) of acid blue 9 dye infiltration in 'Palmer' mangoes treated or not with hot-air heating (45 °C) under different immersion times in cold water at 6.0 °C.

Immersion time (minutes)	Treatments	
	Hot-air heating 45 °C	Control ~25 °C
0	0.0 ± 0.0 cA	0.0 ± 0.0 eA
5	1.8 ± 0.2 bA	0.0 ± 0.0 eB
15	3.0 ± 0.1 aA	0.3 ± 0.1 dB
30	2.9 ± 0.2 aA	0.8 ± 0.1 cB
45	3.0 ± 0.2 aA	1.4 ± 0.1 bB
60	2.9 ± 0.2 aA	1.8 ± 0.1 aB
SD (%)	2.3	0.7

Means followed by the same letters, lowercase within the columns (immersion times) and uppercase within a row (with and without heating), do not differ from each other according to the Tukey test ($p < 0.05$).

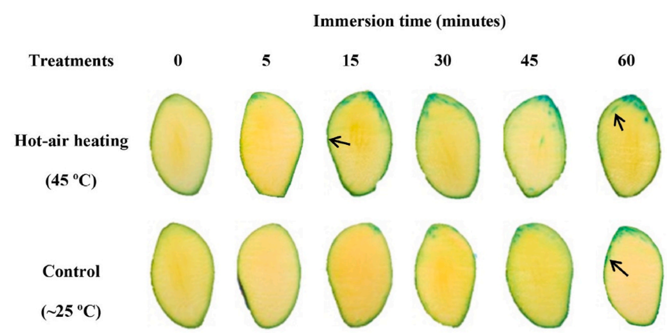

Fig. 1. Acid blue 9 dye infiltration in 'Palmer' mangoes treated with hot-air heating (45 °C) or not (control) under different immersion times in cold water at 6.0 °C. The arrows indicate the dye infiltration in the pericarp and mesocarp.

4. Conclusions

Hot-air heating of 'Palmer' mangoes for 15 min was sufficient to achieve maximum dye absorption, indicating the potential for hydrocooling water infiltration. Regardless of the cooling duration, dye absorption occurred consistently through the lenticels on the skin and occasionally through the stem into the mesocarp. The process of hot-air heating, when followed by immersion in cold water, promotes rapid water absorption. If the cooling water is inadequately treated, there is a potential risk for the internalization of food-borne pathogens. Implementing appropriate measures to ensure water safety during hydrocooling is therefore strongly recommended to protect the quality and safety of the mangoes.

CRediT authorship contribution statement

Alex Guimarães Sanches: Writing – original draft, Methodology, Investigation, Formal analysis. **Maryelle Barros da Silva:** Investigation, Formal analysis. **Vanessa Maria Dantas Pedrosa:** Investigation, Formal analysis. **Thiago Feliph Silva Fernandes:** Investigation, Formal analysis. **Maria Carolina Casares Wong:** Investigation, Formal analysis. **Priscila Lupino Gratão:** Visualization, Supervision. **Gustavo Henrique de Almeida Teixeira:** Writing – original draft, Visualization, Project administration, Funding acquisition, Data curation, Conceptualization.

Consent to participate

Informed consent was obtained from all individual participants included in the study.

Ethics approval consent

Not applicable.

Funding

Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP), project number 2019/15116-0. Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) first author scholarship (142125/2019-9) and Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) - Financial Code 001.

Declaration of competing interest

none.

Acknowledgments

The authors wish to extend their sincere appreciation to Mr. Hermes Pinhatti and Mr. Rodrigo Pinhatti for generously providing the fruits utilized in this study.

Data availability

Data will be provided upon request.

References

[1] S. Javed, H. Fu, A. Ali, A. Nadeem, M. Amin, K. Razzaq, S.B. Hussain, Comparative response of mango fruit towards pre- and post-storage quarantine heat treatments, Agronomy 12 (2022) 1476, https://doi.org/10.3390/agronomy12061476.

[2] K.K. Jacobi, E.A. MacRae, S.E. Hetherington, Loss of heat tolerance in 'Kensington' mango fruit following heat treatments, Postharvest Biol. Technol. 21 (2001) 321–330, https://doi.org/10.1016/S0925-5214(00)00180-0.

[3] Y. Duan, G.B. Wang, O.A. Fawole, P. Verboven, X.R. Zhang, D. Wu, U.L. Opara, B. Nicolai, K. Chen, Postharvest precooling of fruit and vegetables: a review, Trends Food Sci. Technol. 100 (2020) 278–291, https://doi.org/10.1016/j.tifs.2020.04.027.

[4] J.A. Bartz, R. Showalter, Infiltration of tomatoes by aqueous bacterial suspensions, Phytopathol 71 (1981) 515–518.

[5] A. Warning, A.K. Datta, J.A. Bartz, Mechanistic understanding of temperature-driven water and bacterial infiltration during hydrocooling of fresh produce, Postharvest Biol. Technol. 118 (2016) 159–174, https://doi.org/10.1016/j.postharvbio.2016.03.018.

[6] M.C. Erickson, Internalization of fresh produce by foodborne pathogens, Annu. Rev. Food Sci. Technol. 3 (2012) 283–310, https://doi.org/10.1146/annurev-food-022811-101211.

[7] D. Macarisin, A. Wooten, A. Jesus, M. Hur, S. Bae, J. Patel, P. Evans, E. Brown, T. Hammack, Y. Chen, Internalization of *Listeria monocytogens* in cantaloupes during dump tank washing and hydrocooling, Int. J. Food Microbiol. 257 (2017) 165–175, https://doi.org/10.1016/j.ijfoodmicro.2017.06.018.

[8] A.A.N. Gunny, S.C. Gopinath, A. Ali, C. Wongs-Aree, N.H.M. Salleh, Challenges of postharvest water loss in fruits: mechanisms, influencing factors, and effective control strategies–a comp, Review, J. Agric. Food Res. 17 (2024) 101249, https://doi.org/10.1016/j.jafr.2024.101249.

[9] P. Kaur, S. Kaur, P. Aggarwal, A. Kumar, Post harvest hot water immersion treatment as sustainable approach for artificial curing of immature dates to reduce wastage, Food Chem. 467 (2024) 142157, https://doi.org/10.1016/j.foodchem.2024.142157.

[10] P. Fatemi, L.F. Laborde, J. Patton, G.M. Sapers, B. Annous, S.J. Knabel, Influence of punctures, cuts, and surface morphologies of golden delicious apples on penetration and growth of *Escherichia coli* O157: H7, J Food Prot 69 (2006) 267–275, https://doi.org/10.4315/0362-028X-69.2.267.

[11] M. Srimartpirom, C. Rakkrai, S. Phankum, R. Intarakamhang, C. Sonsiri, P. Buchatian, P.A. Follett, Vapor heat treatment for quarantine control of the oriental fruit fly (Diptera: tephritidae) in papaya fruit from Thailand, J. Asia Pac. Entomol. 26 (2023) 102049, https://doi.org/10.1016/j.aspen.2023.102049.

[12] K.A. Corey, Z.Y. Tan, Induction of changes in internal gas pressure of bulky plant organs by temperature gradients, J. Am. Soc. Hortic. Sci. 115 (1990) 308–312, https://doi.org/10.21273/JASHS.115.2.308.

[13] H. Rymbai, M. Srivastav, R.R. Sharma, S.K. Singh, Lenticels on mango fruit: origin, development, discoloration and prevention of their discoloration, Sci. Hortic. (Amst.) 135 (2012) 164–170, https://doi.org/10.1016/j.scienta.2011.11.018.

[14] D.C.G. Trindade, M.A.C. Lima, J.S. Assis, 1-methylcyclopropene action on postharvest conservation of 'Palmer' mango fruit a different maturity stage, Pesqui. Agropecu. Bras. 50 (2015) 753–762, https://doi.org/10.1590/S0100-204X2015000900003.

[15] R Core Team, R: a language and environment for statistical computing. https://www.R-project.org/, 2020. (Accessed 12 December 2023), 2023.

[16] A.L. Penteado, B.S. Eblen, A.J. Miller, Evidence of *Salmonella* internalization into fresh mangos during simulated postharvest insect disinfestation procedures, J Food Prot 67 (2024) 181–184, https://doi.org/10.4315/0362-028X-67.1.181.

[17] B.S. Eblen, M.O. Walderhaug, S. Edelson-Mammel, S.J. Chirtel, A. De Jesus, R. I. Merker, A.J. Miller, Potential for internalization, growth, and survival of Salmonella and *Escherichia coli* O157: H7 in oranges, J Food Prot 67 (2004) 1578–1584, https://doi.org/10.4315/0362-028x-67.8.1578.

[18] M. Mohammed, A.J.A.M. Jawad, A.M. Mohammed, J.K. Oleiwi, T. Adam, A. F. Osman, O.S. Dahham, B.O. Betar, S.C.B. Gopinath, M. Jaafar, Challenges and advancement in water absorption of natural fiber-reinforced polymer composites, Polym. Test. 124 (2023) 108083, https://doi.org/10.1016/j.polymertesting.2023.108083.

[19] V. Paul, S.K. Malik, G.C. Srivastava, Intervarietal differences in the surface morphology and anatomy of mango (*Mangifera indica* L.) fruit, Phytomorphology 57 (2007) 211–218.

[20] S.E.S.A. Khader, D.K. Tandon, S.K. Kalra, Epicuticular wax and lenticel changes during development of mango fruit cv. Dashehari, Indian J. Hortic. 49 (1992) 165–168. https://www.indianjournals.com/ijor.aspx?target=ijor:ijh&volume=49&issue=2&article=010.